# A Scalable 6-to-18GHz Concurrent Dual-Band Quad-Beam Phased-Array Receiver in CMOS

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# Outline

- **Introduction**
- Proposed Concurrent Phased-Array System
- 6-to-18GHz Phased-Array Receiver
- Test Setups and Experimental Results
- Conclusion

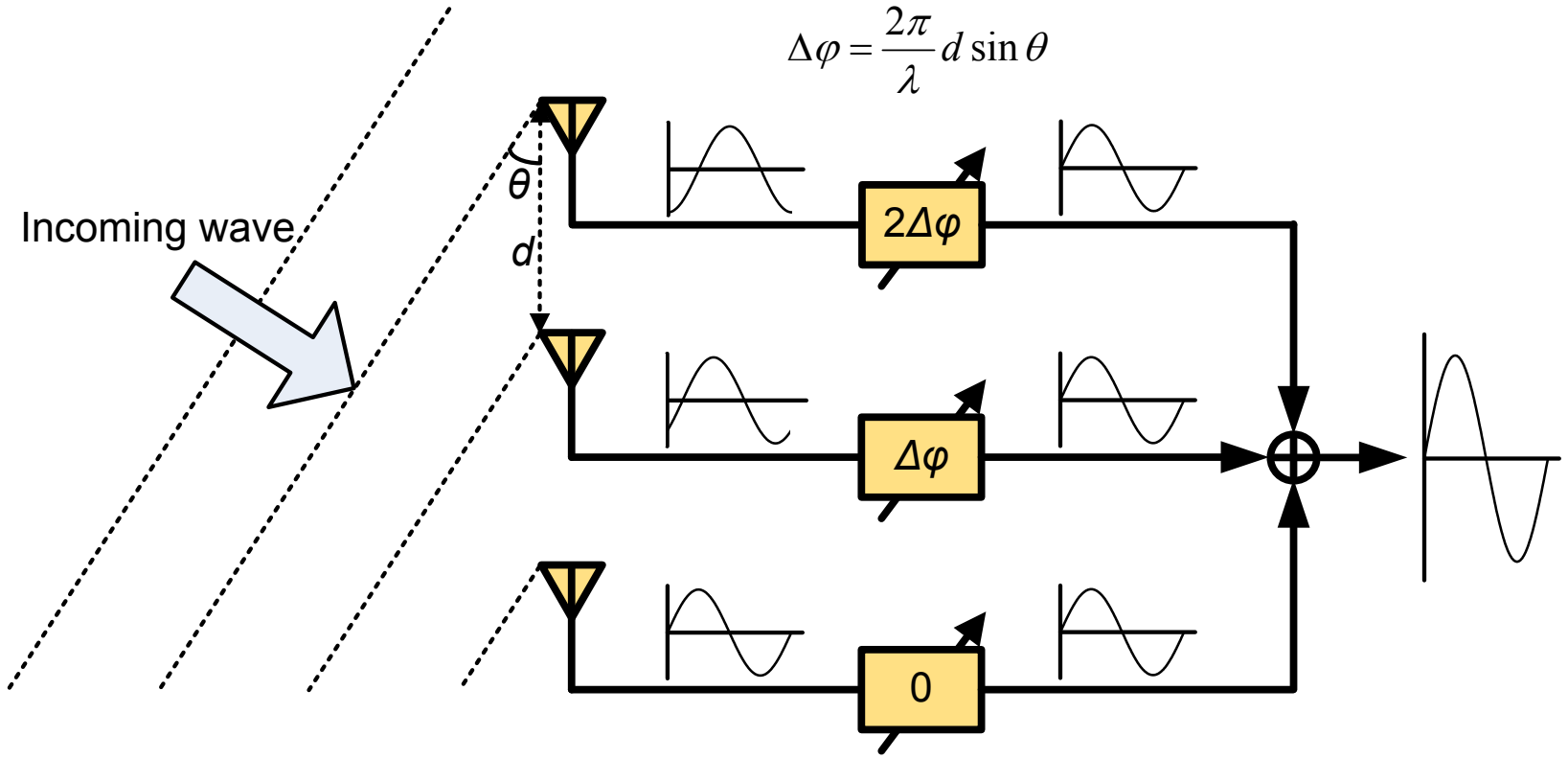
# Wideband Large-Scale Phased Arrays

Military radars

Space & satellite communications

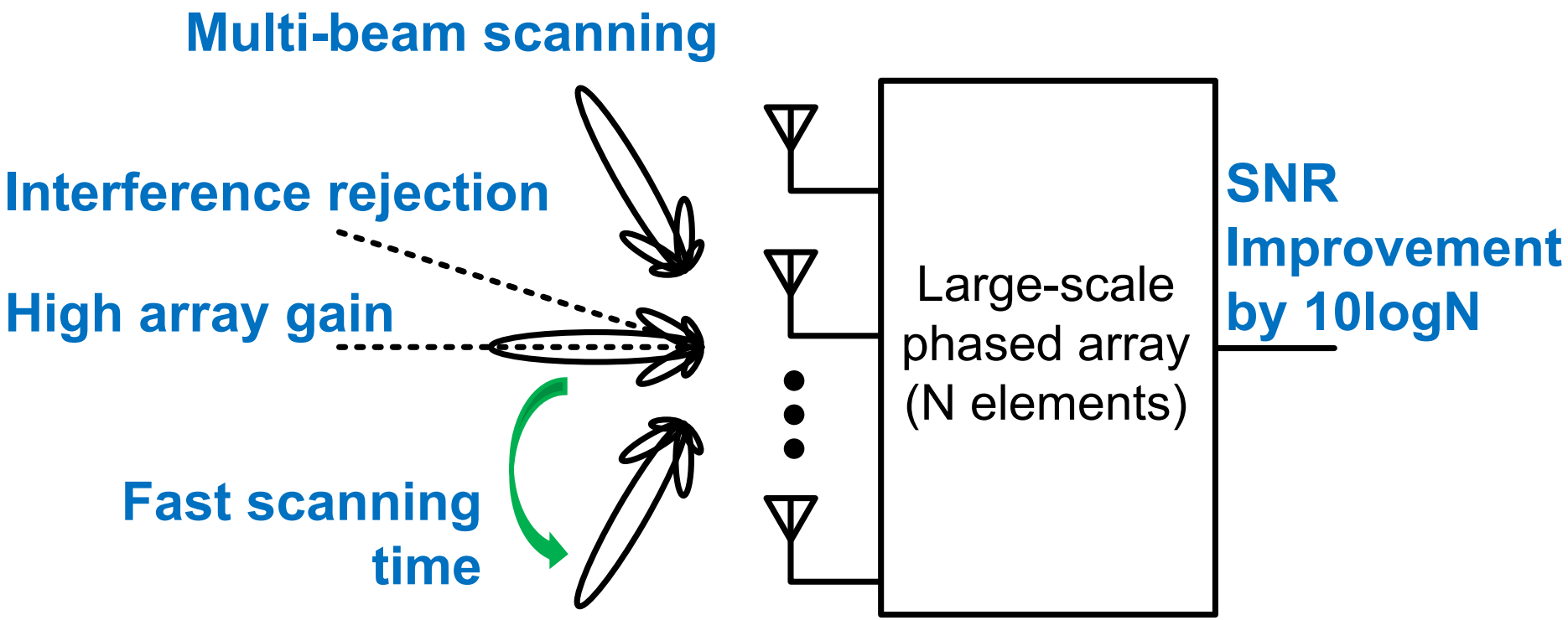
Weather radars

# Phased Arrays

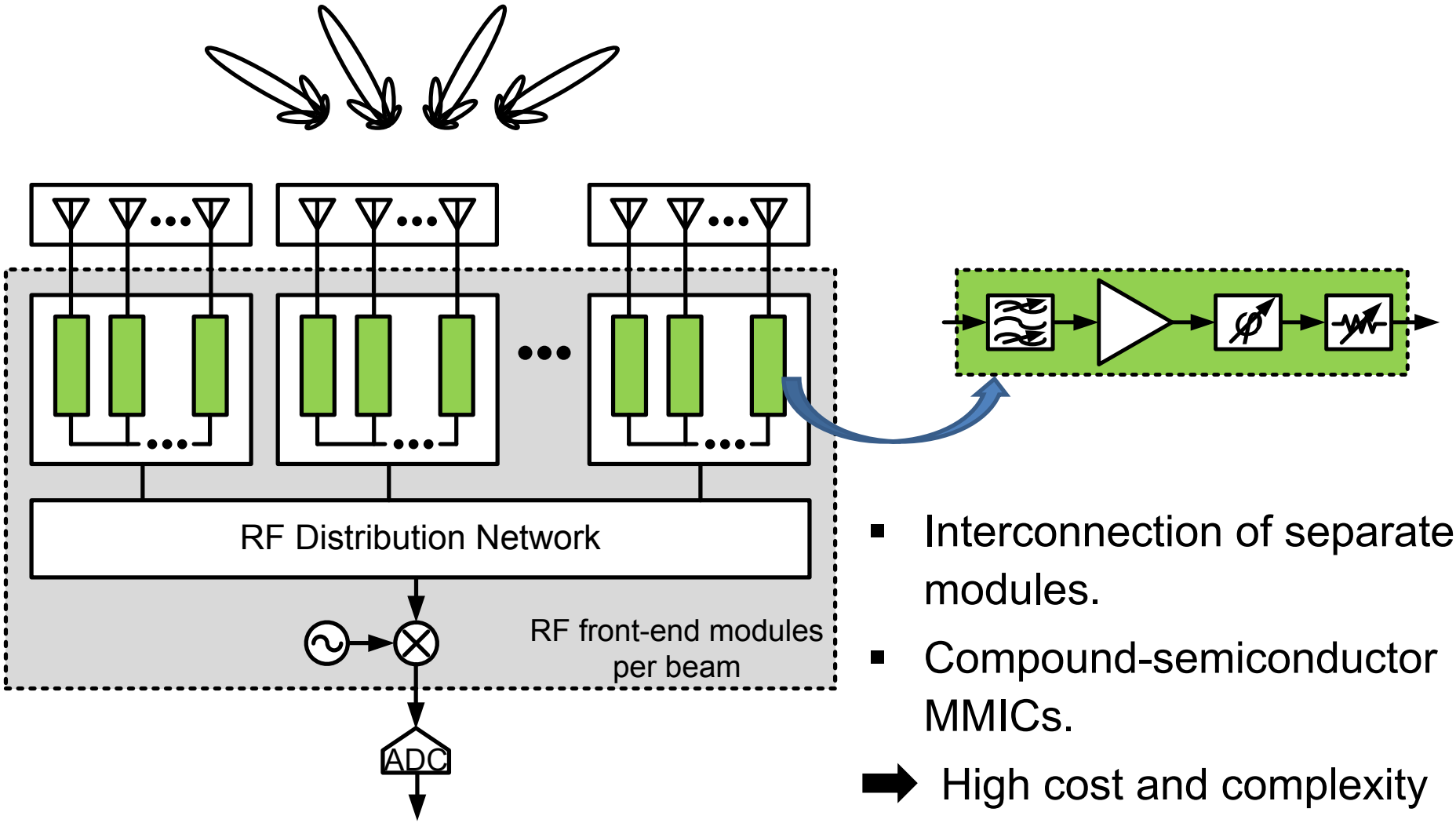



- Coherent addition of signals from each element.
- Reject other signals with different incident angles.

# Advantages of Phased Arrays



# Conventional Structure of Large-Scale Arrays




- Interconnection of separate modules.
- Compound-semiconductor MMICs.

➡ High cost and complexity

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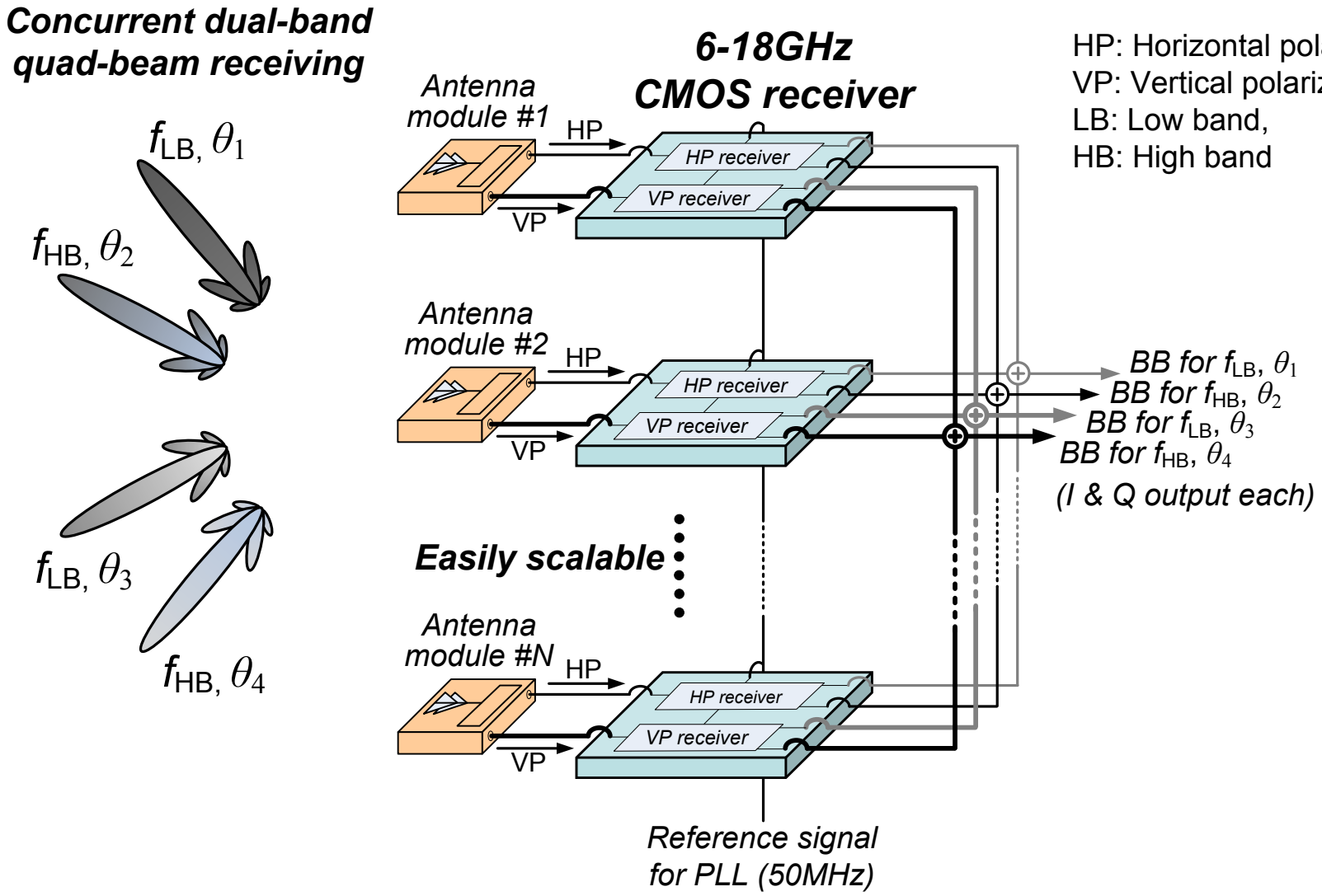
# Tunable Concurrent Multi-Beam Array

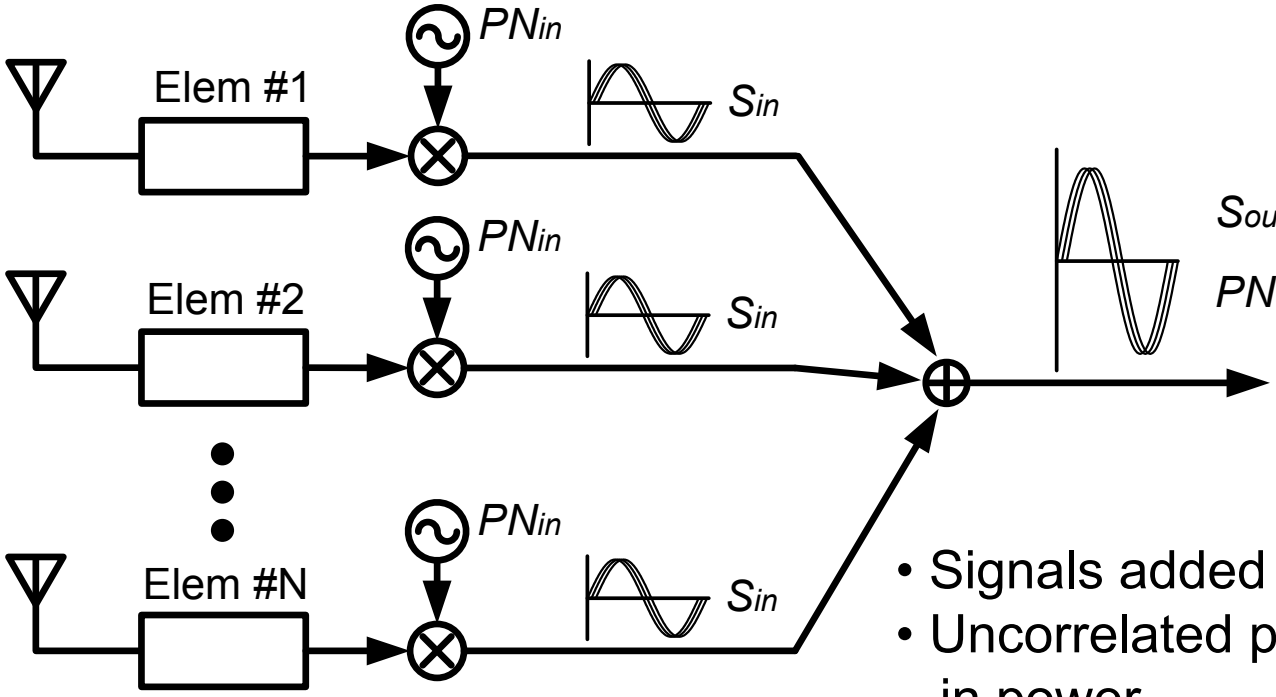



- Required components reduced dramatically.

# Features of Proposed Concurrent Array

- Easily scalable to build large-scale arrays.
  - Dramatically reduce number of components required.
  - Low cost, low complexity, more reliability.
- Wideband operation (6 – 18GHz)
- Concurrent dual-band quad-beam scanning.
  - LB (6 – 10.4GHz) and HB (10.4 – 18GHz)
  - Two polarizations.
- Phase noise improvement in large-scale arrays.

# Phase Noise Improvement




- Signals added up in current domain.
- Uncorrelated phase noise added up in power.

- Phase noise improved by $10\log_{10}N$.
- On-chip frequency synthesizers acceptable for the phase noise requirement.

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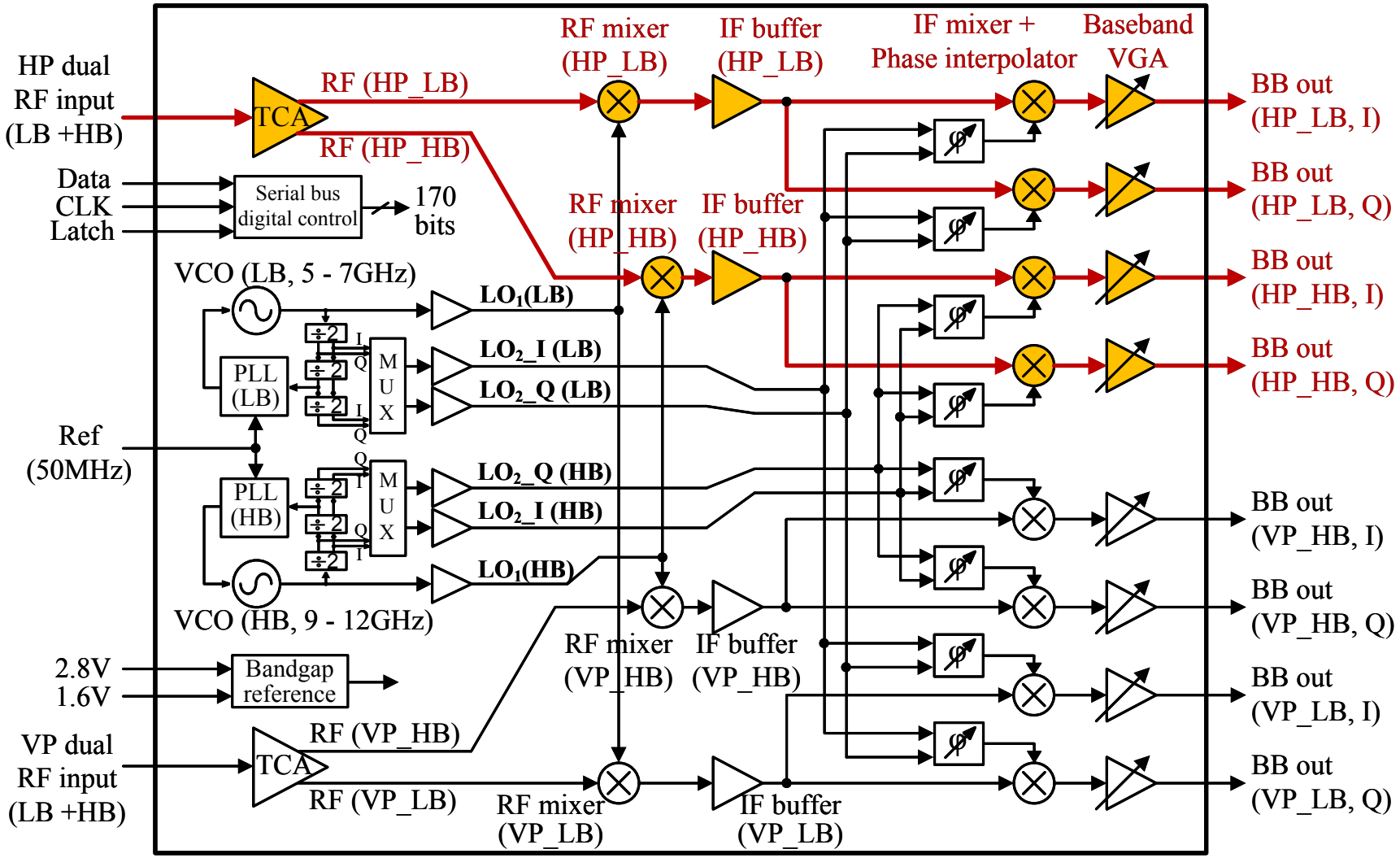
# Receiver Architecture

**HP: Horizontal polarization, VP: Vertical polarization, LB: Low band, HB: High band**



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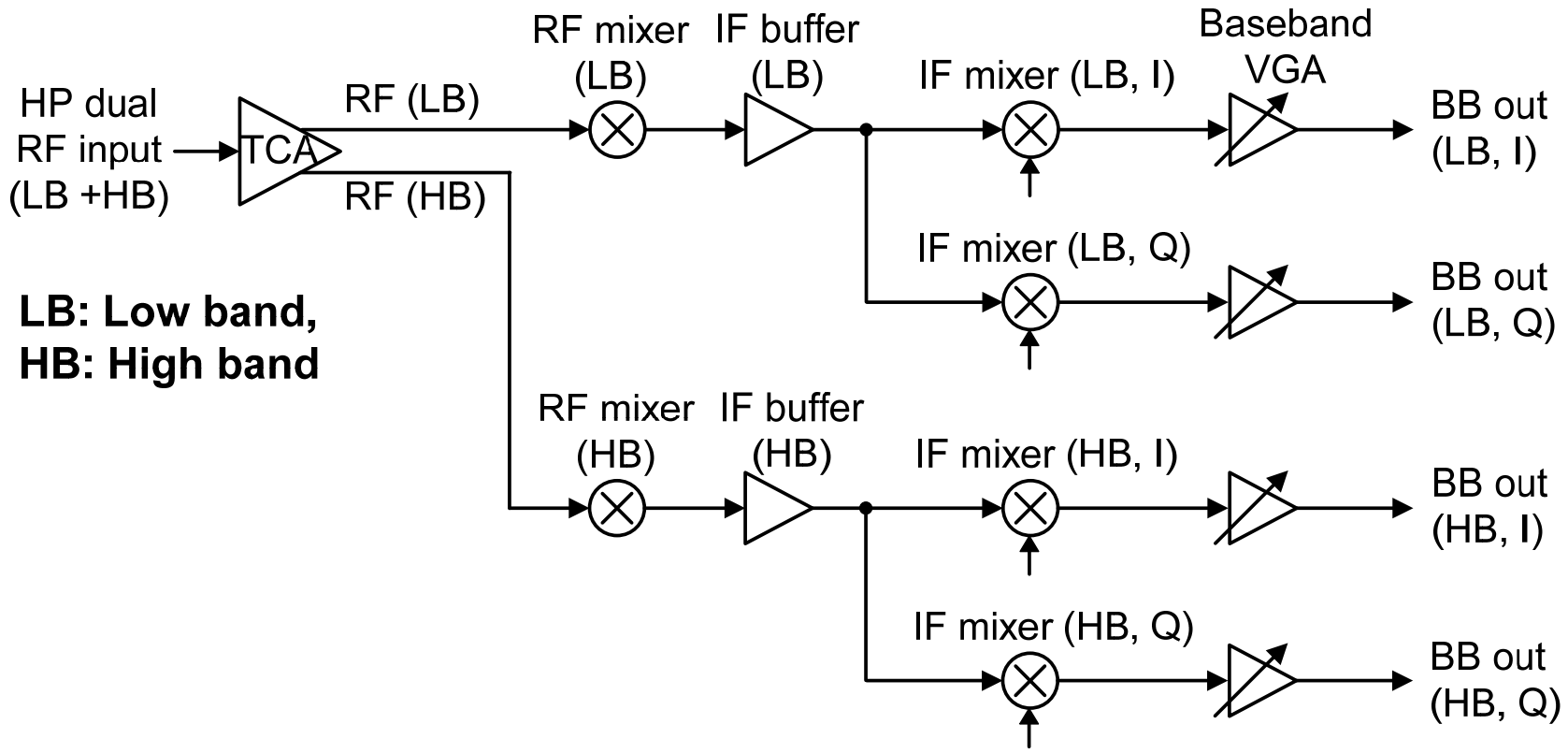

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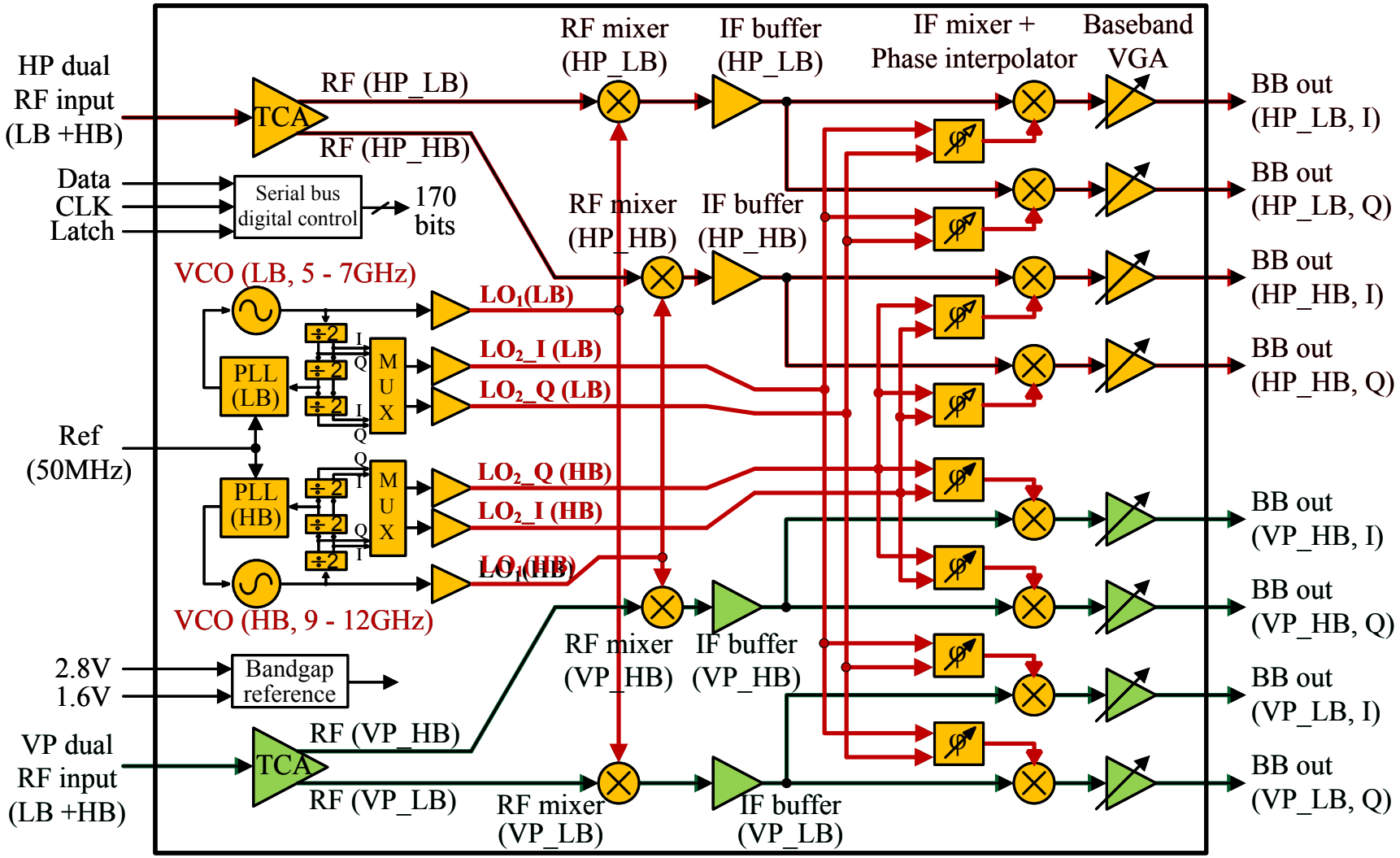

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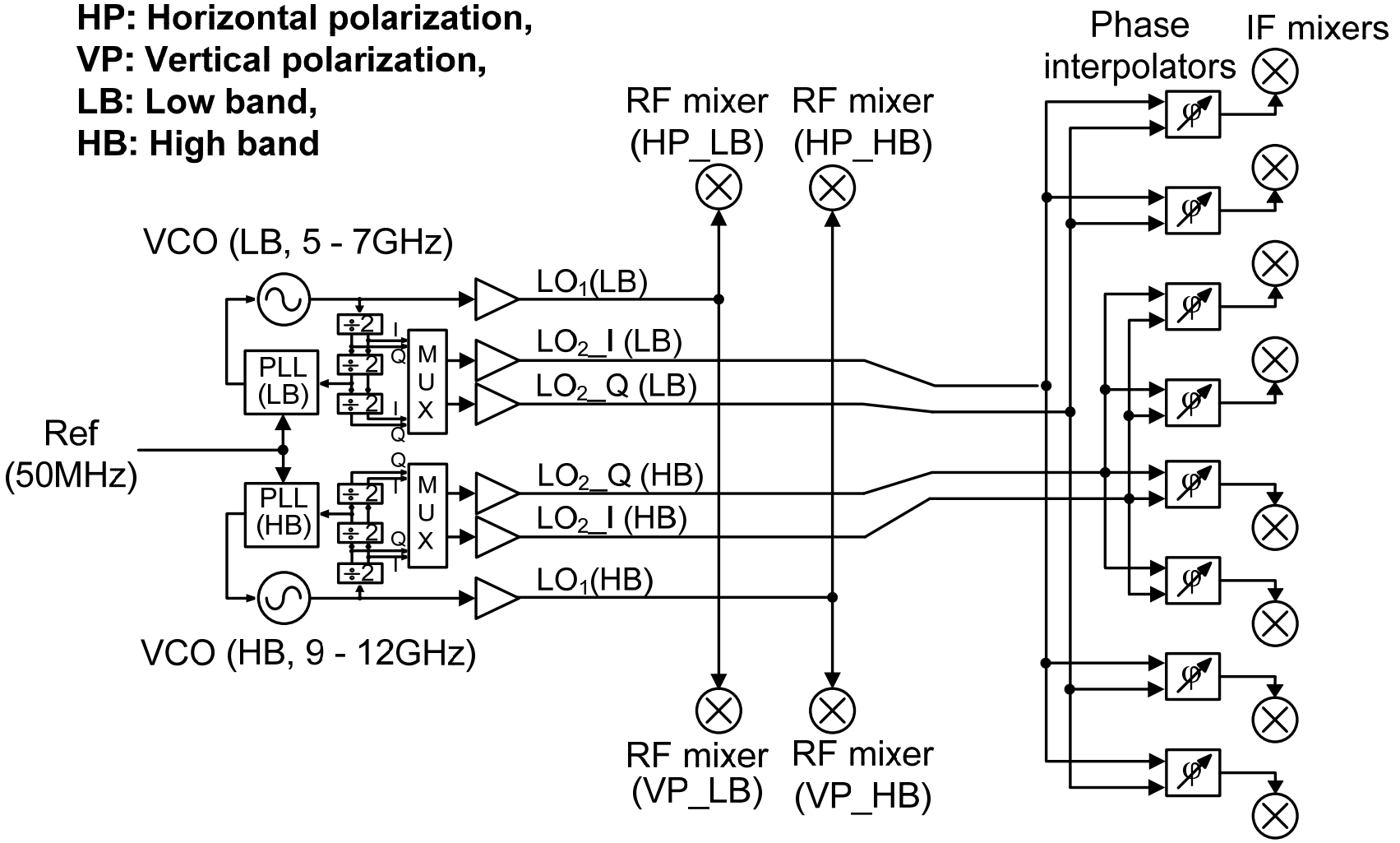

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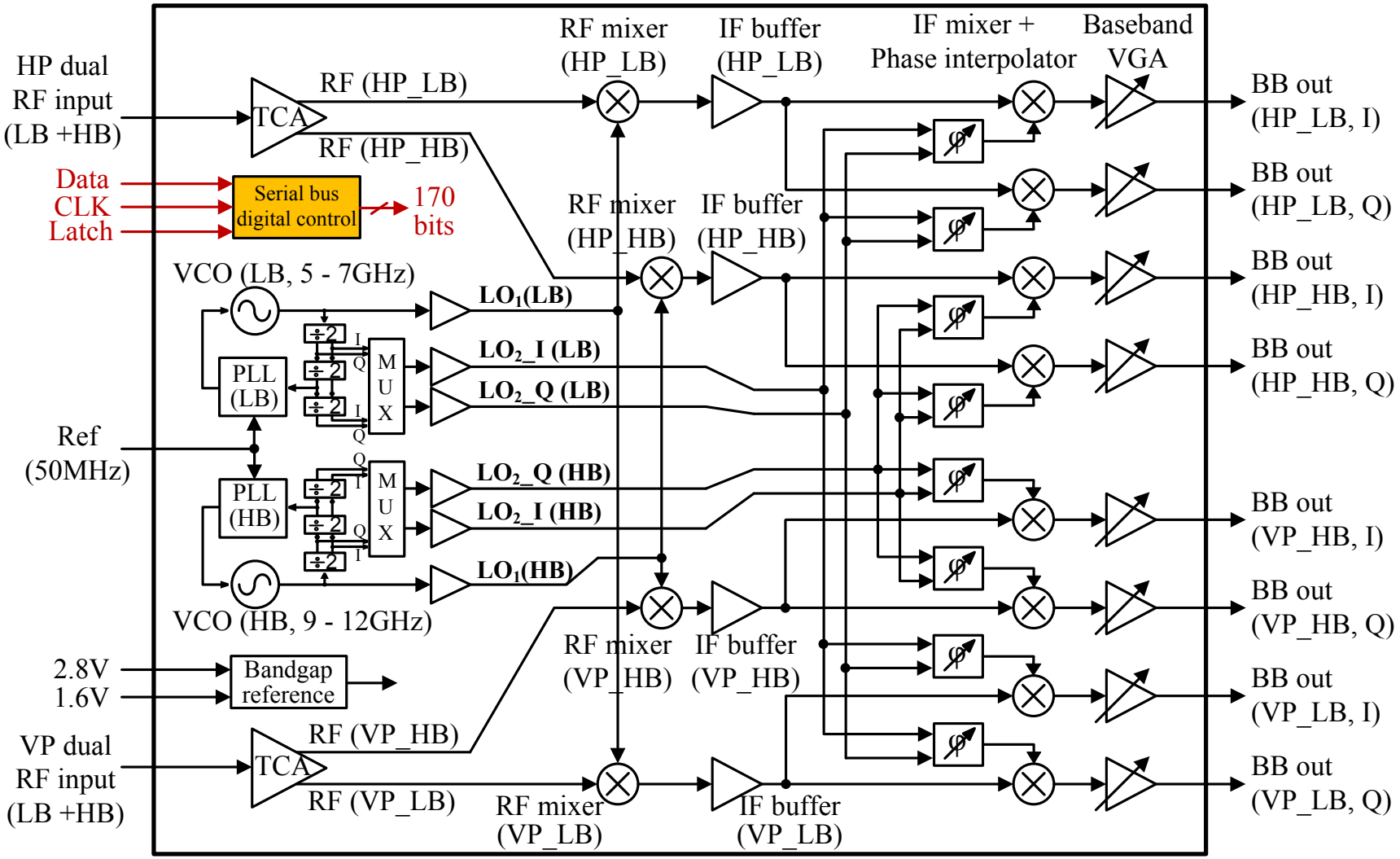
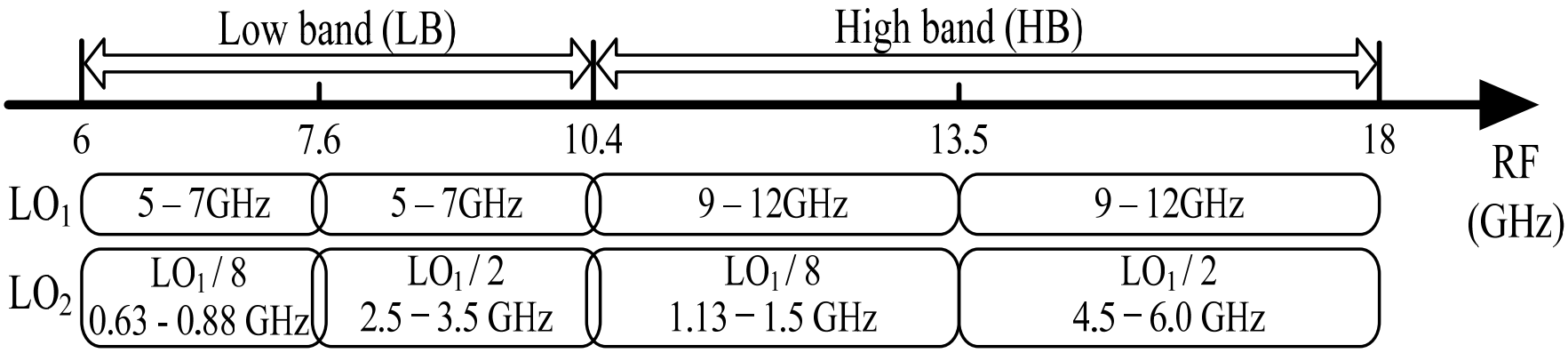
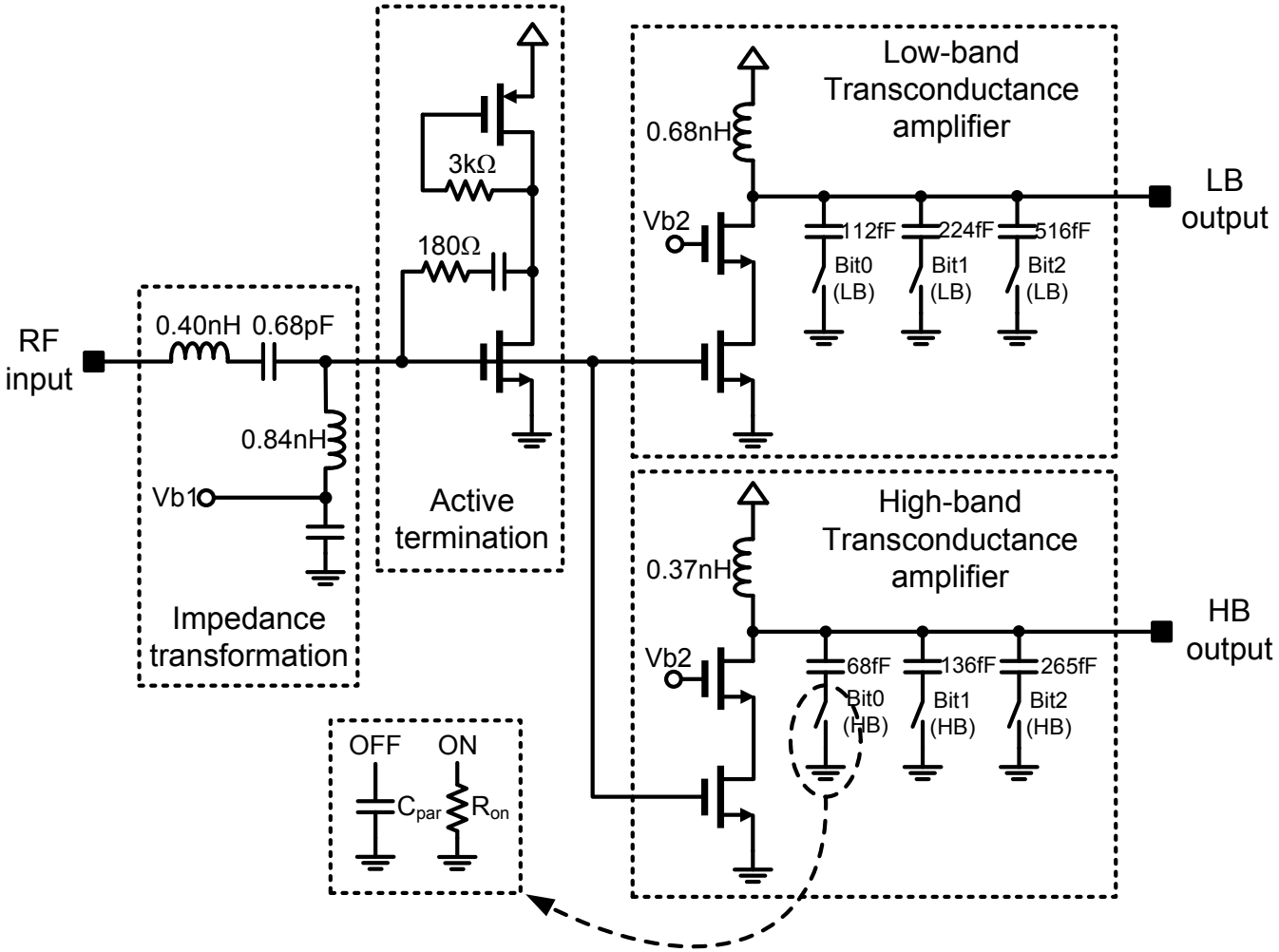


# Frequency Plan



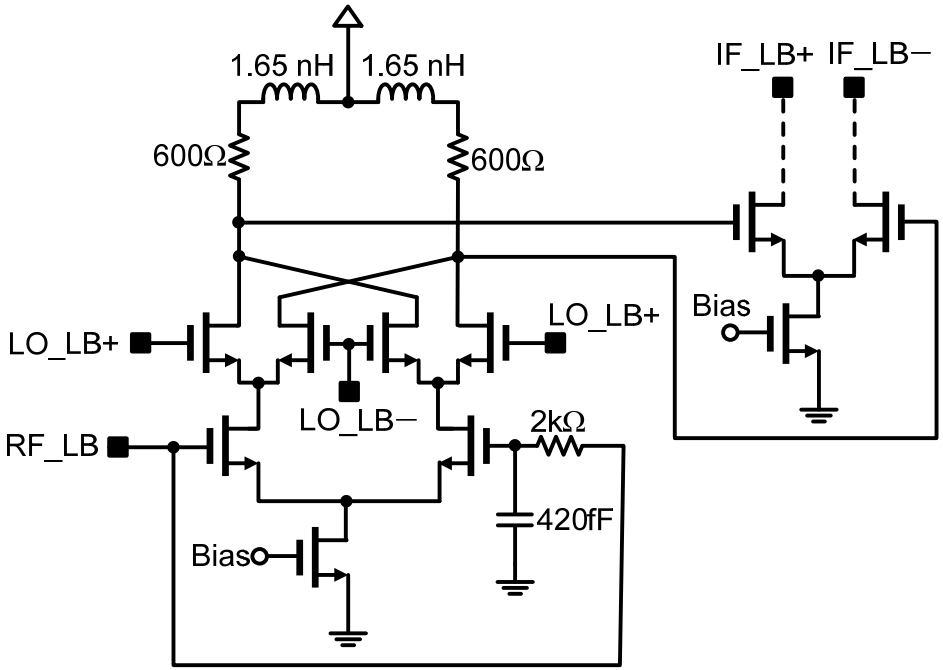

- LO2 switches between 1/2 and 1/8 of LO1, depending on IF frequency.
  - Performed by on-chip multiplexers.
  - Relax the required VCO tuning range.

# Tunable Concurrent Amplifier (TCA)

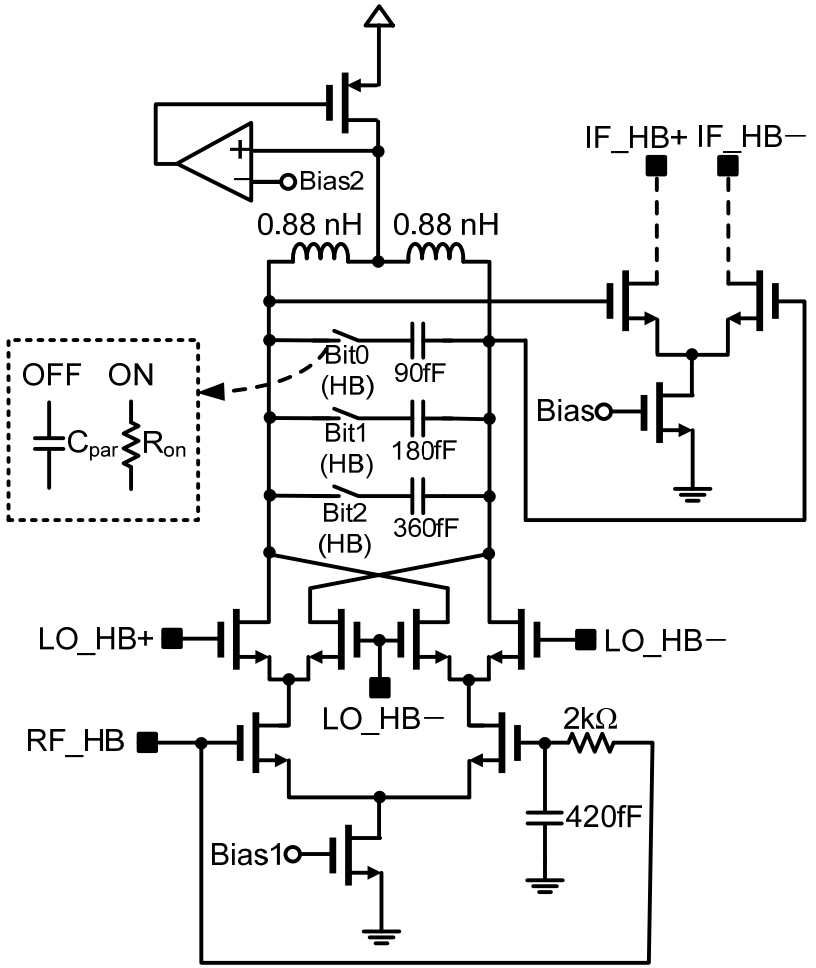



- Single-input, dual-output.
- Tunable LC loads for two separate tuned amplifiers.

# Mixers




LB RF mixer

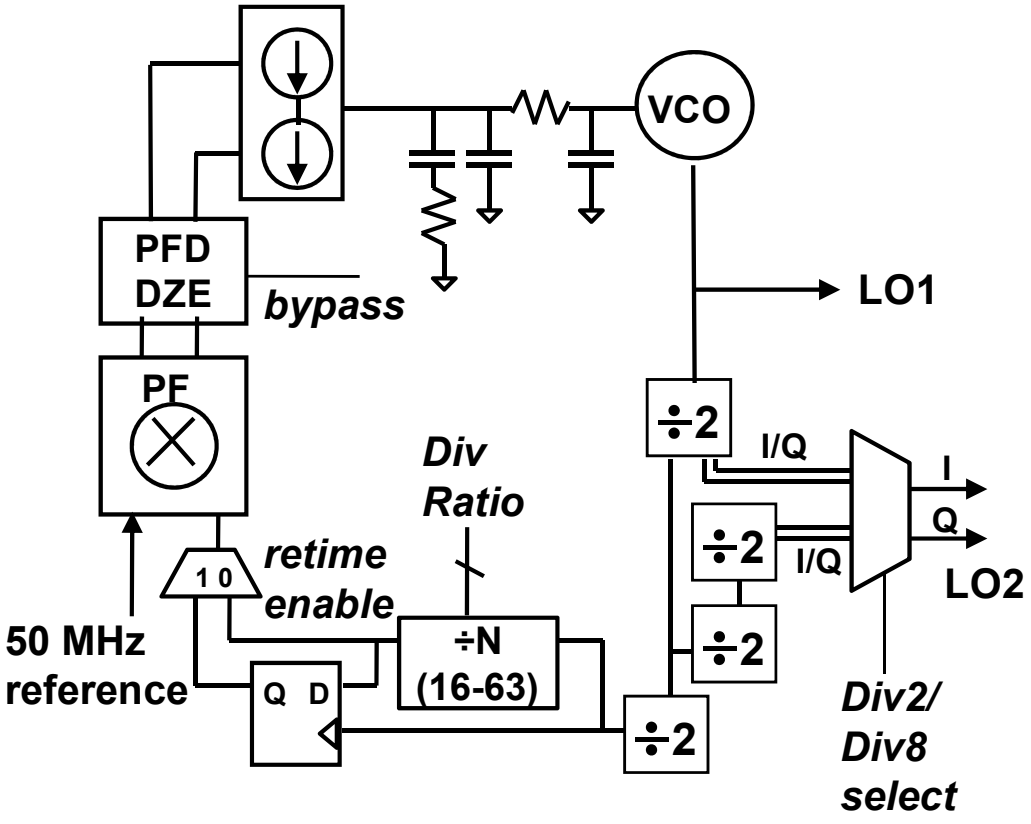



HB RF mixer

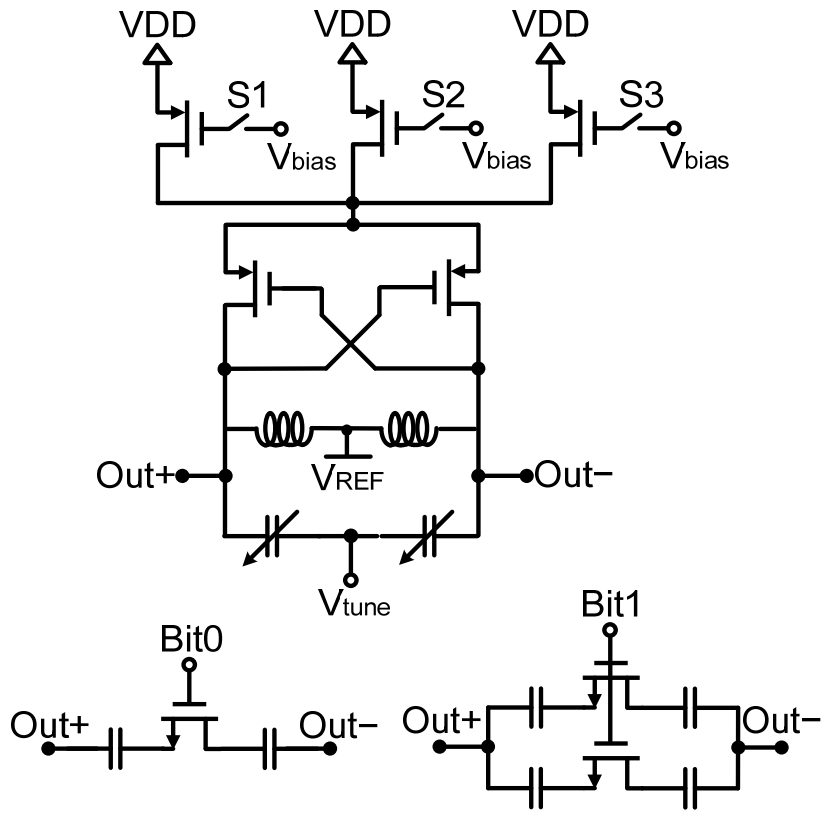
- Current commuting double-balanced mixers.

# Frequency Synthesizers

## Architecture

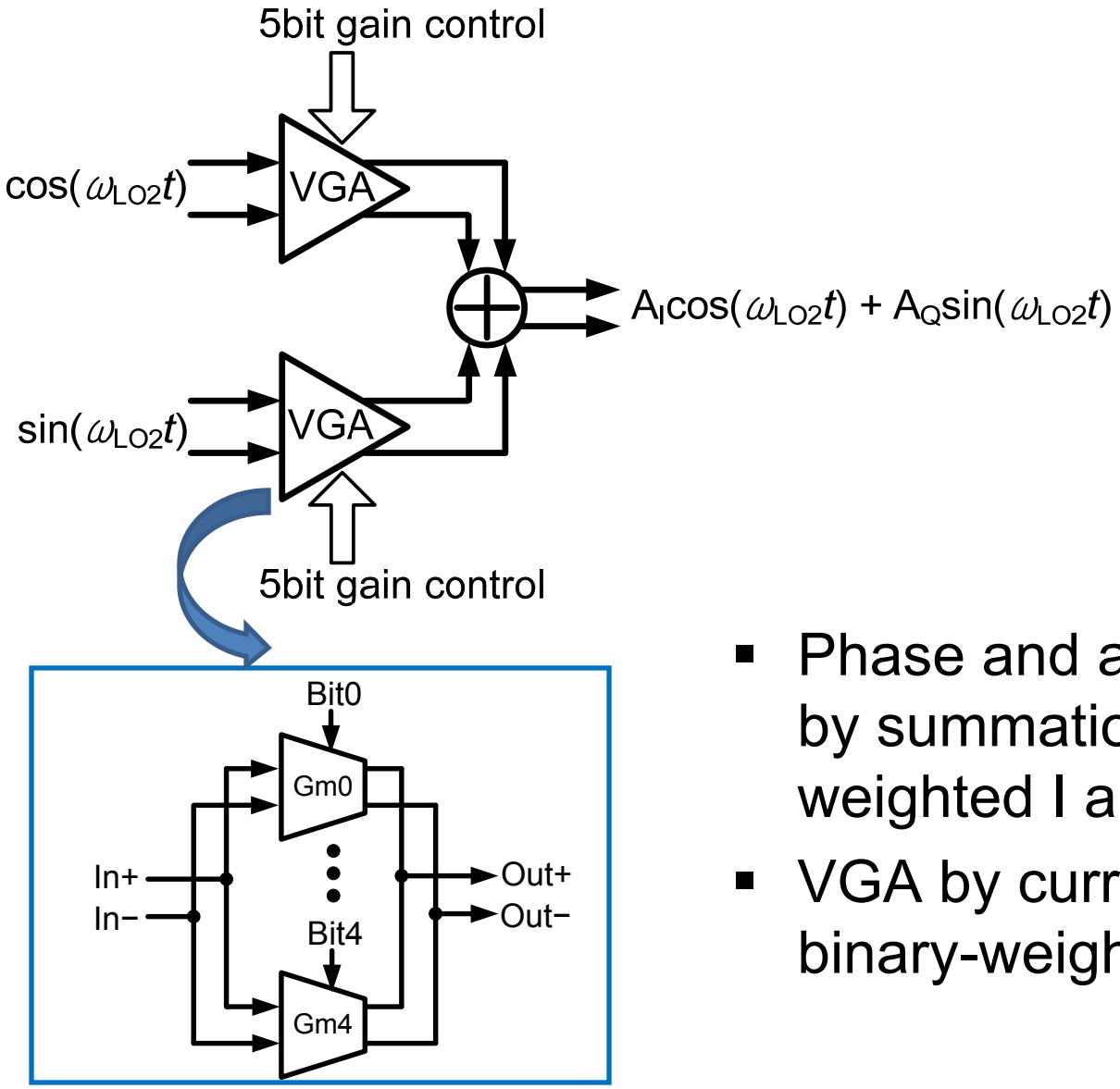


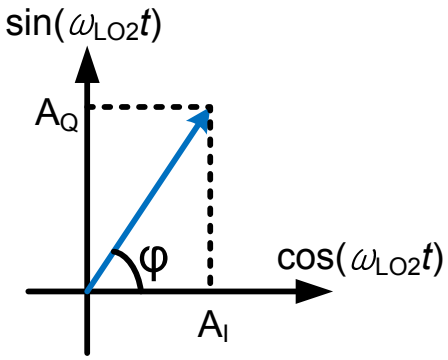

## VCO




- LB: 5 – 7GHz, HB: 9 – 12GHz.
- Frequency generation step: 200MHz.

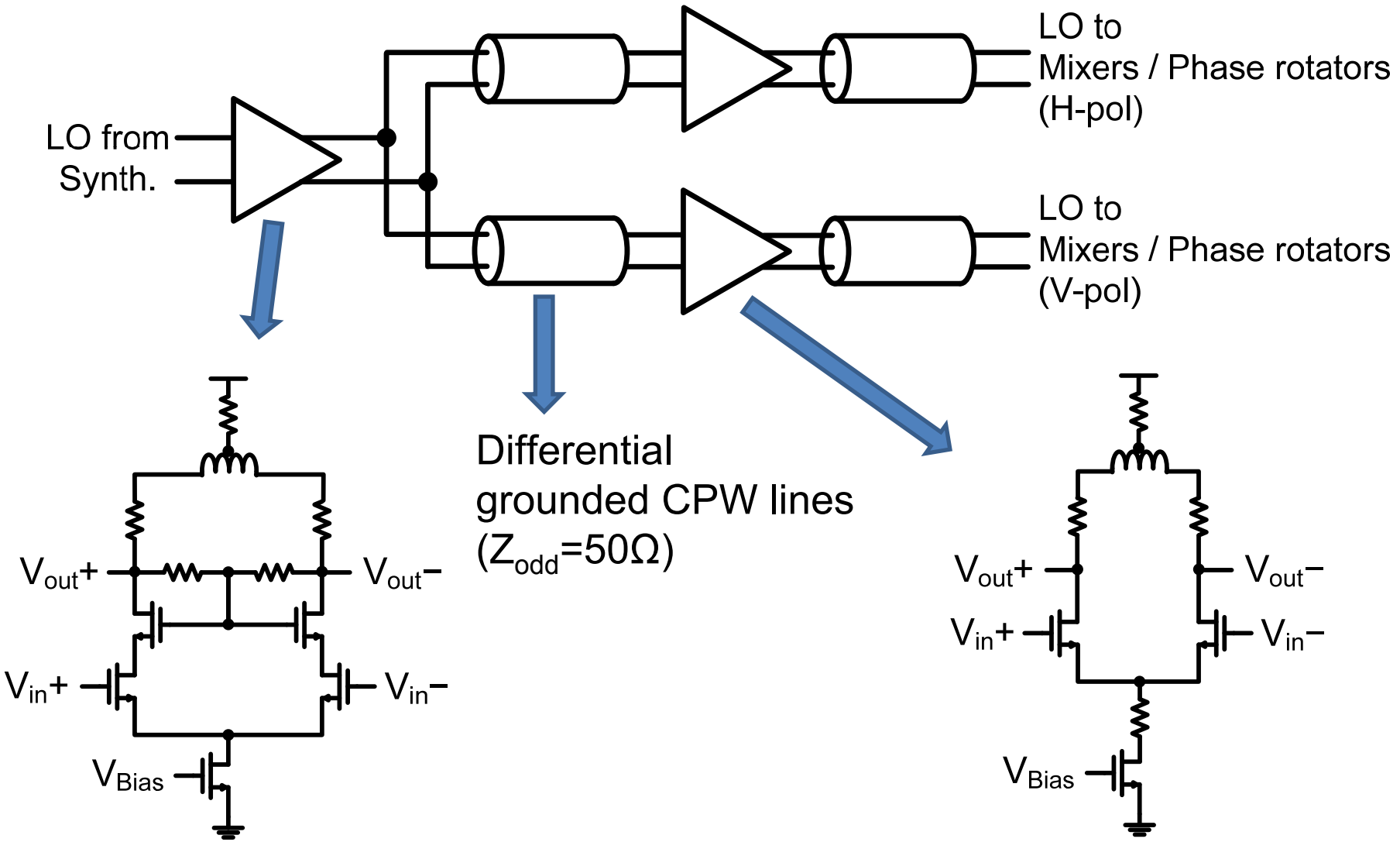
# Digital Phase Rotators



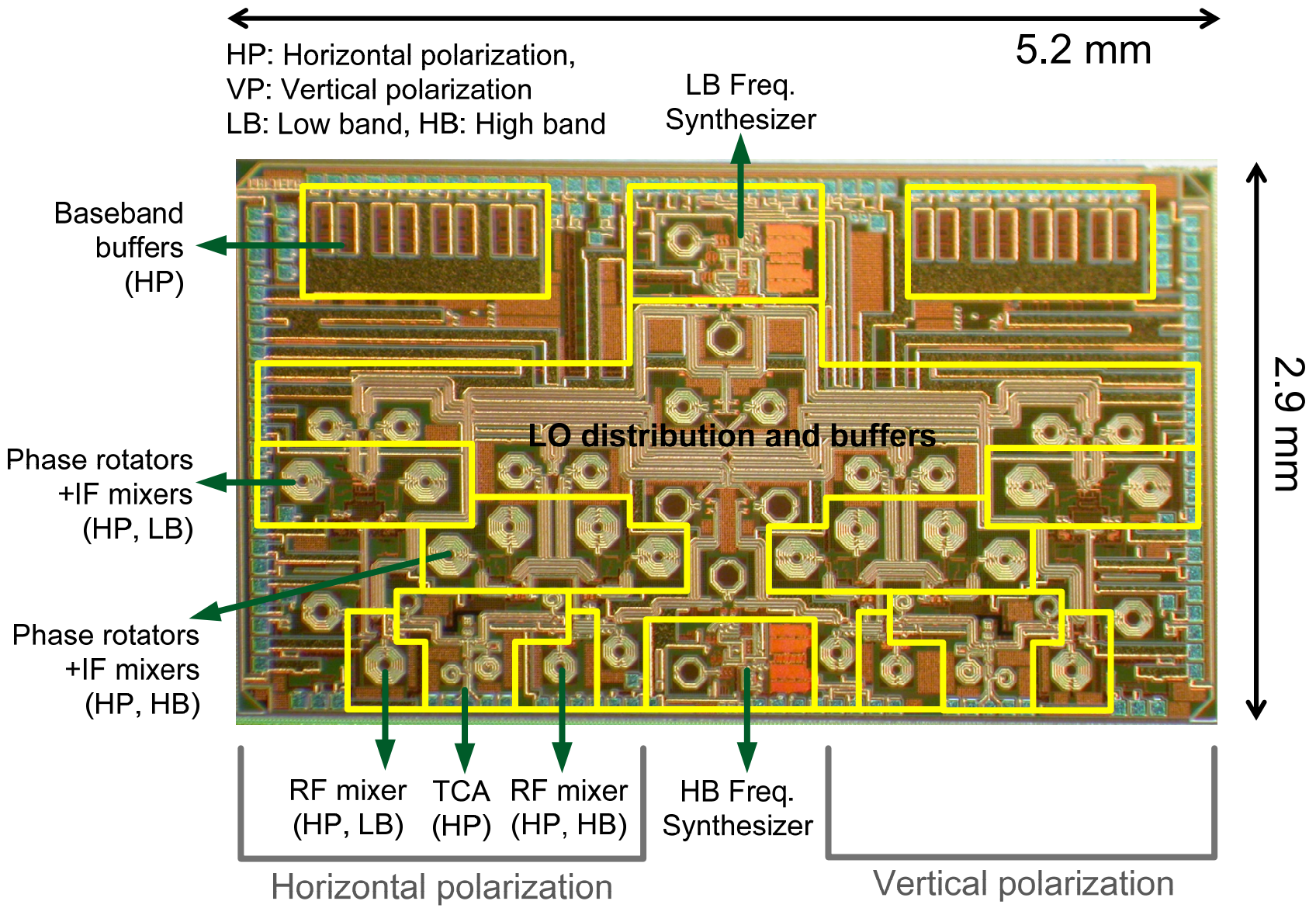




- Phase and amplitude synthesis by summation of differently weighted I and Q.
- VGA by current-combining of binary-weighted Gilbert cells.

# LO Distribution and Buffers



# Chip Photograph



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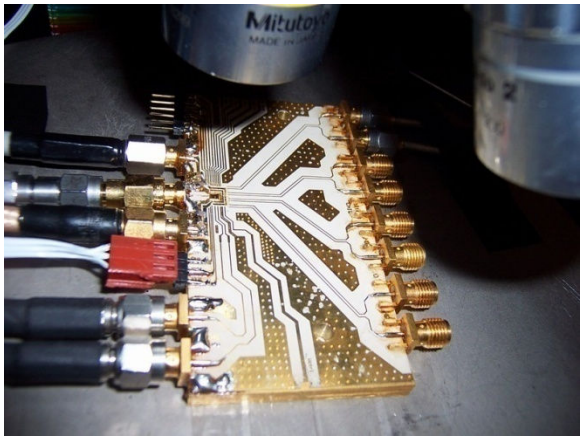
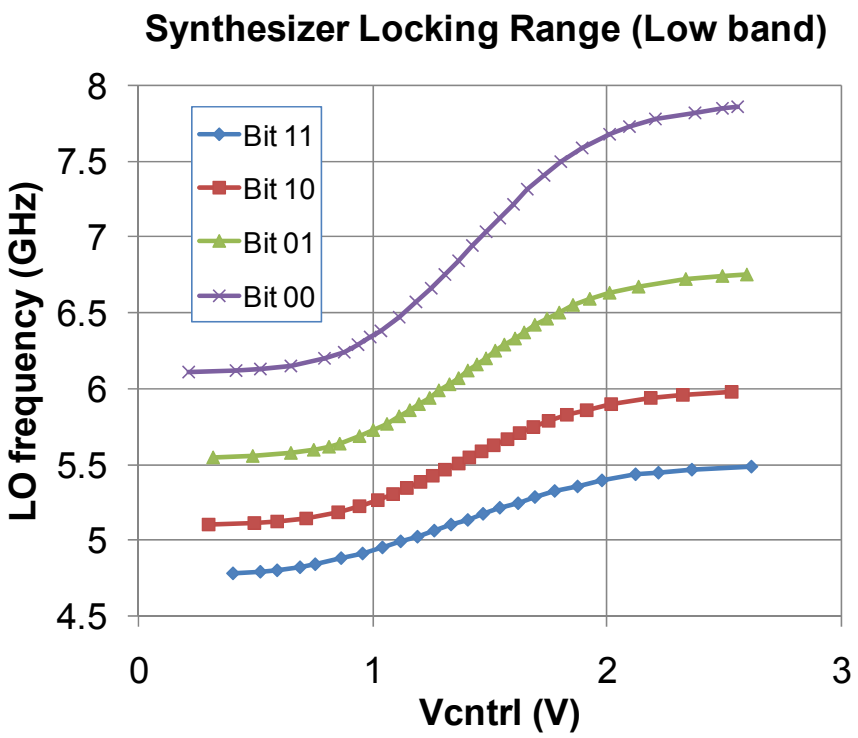
# Test Setup for Receiver Element

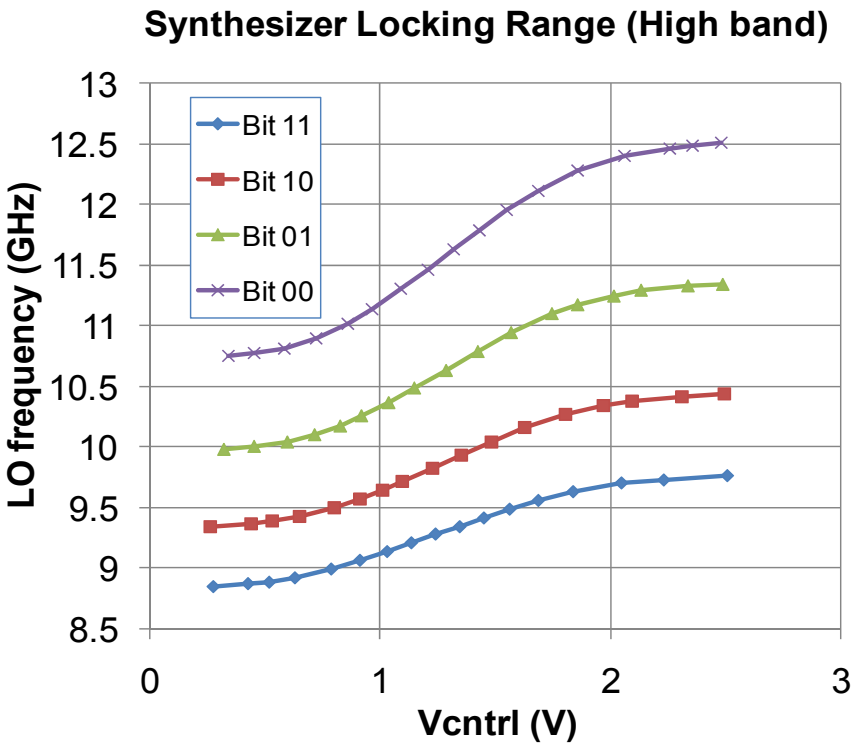





- On-wafer probing for RF input.
- BB output taken differentially and converted to single-ended.

# LO Generation



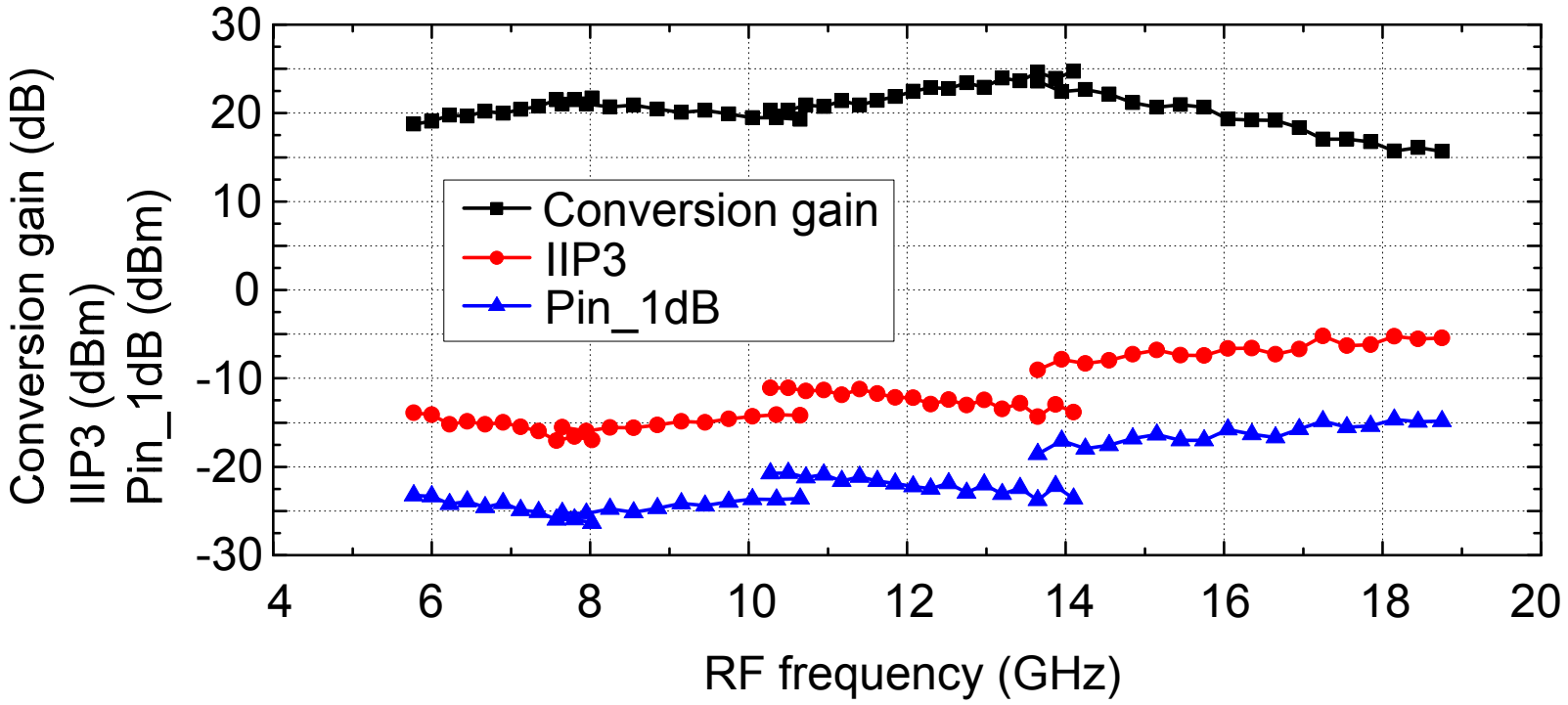

- Locking range:

  4.8 – 7.8GHz

- Locking range:

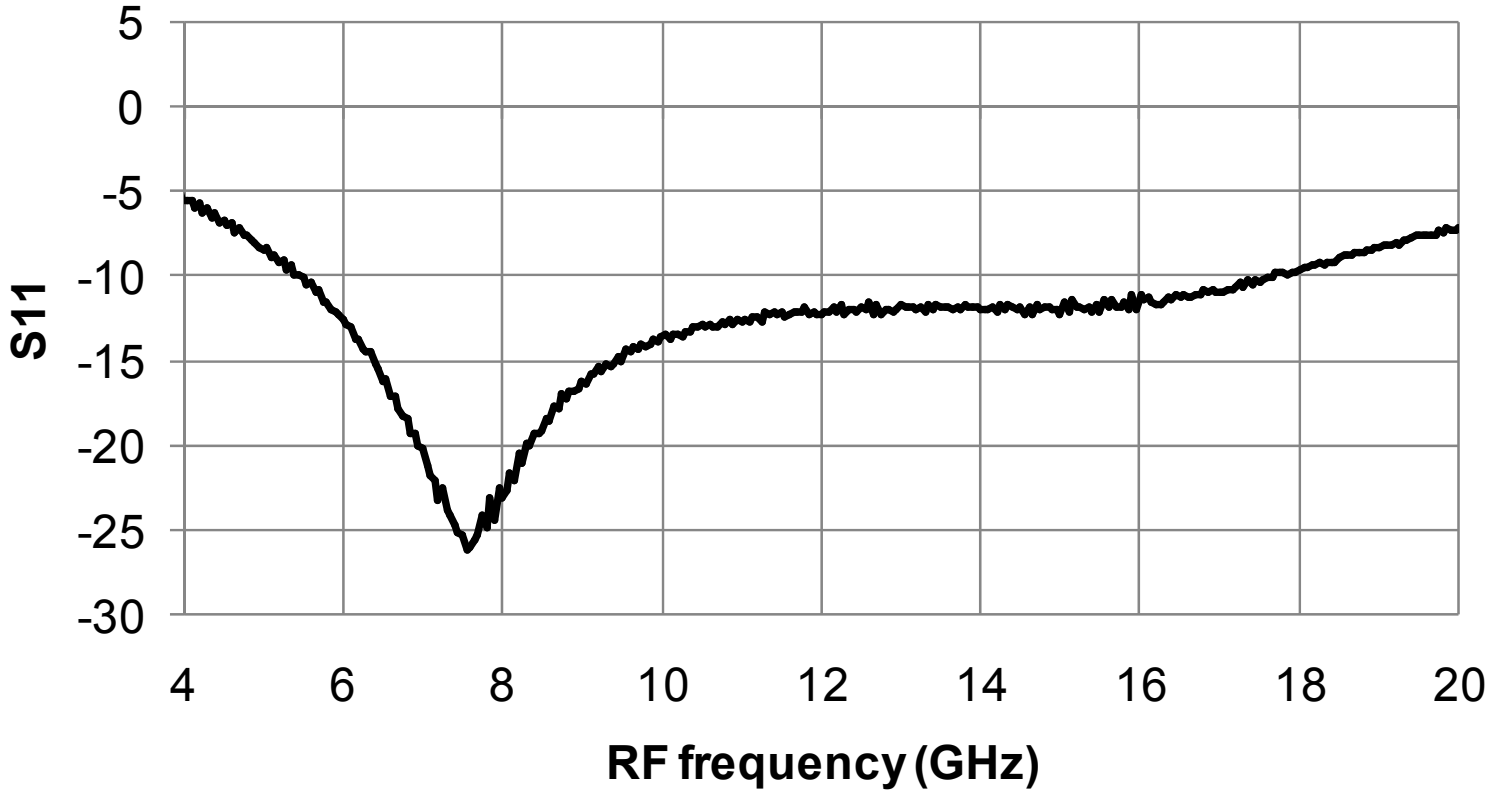
  8.8 – 12.5GHz

# RF Performance



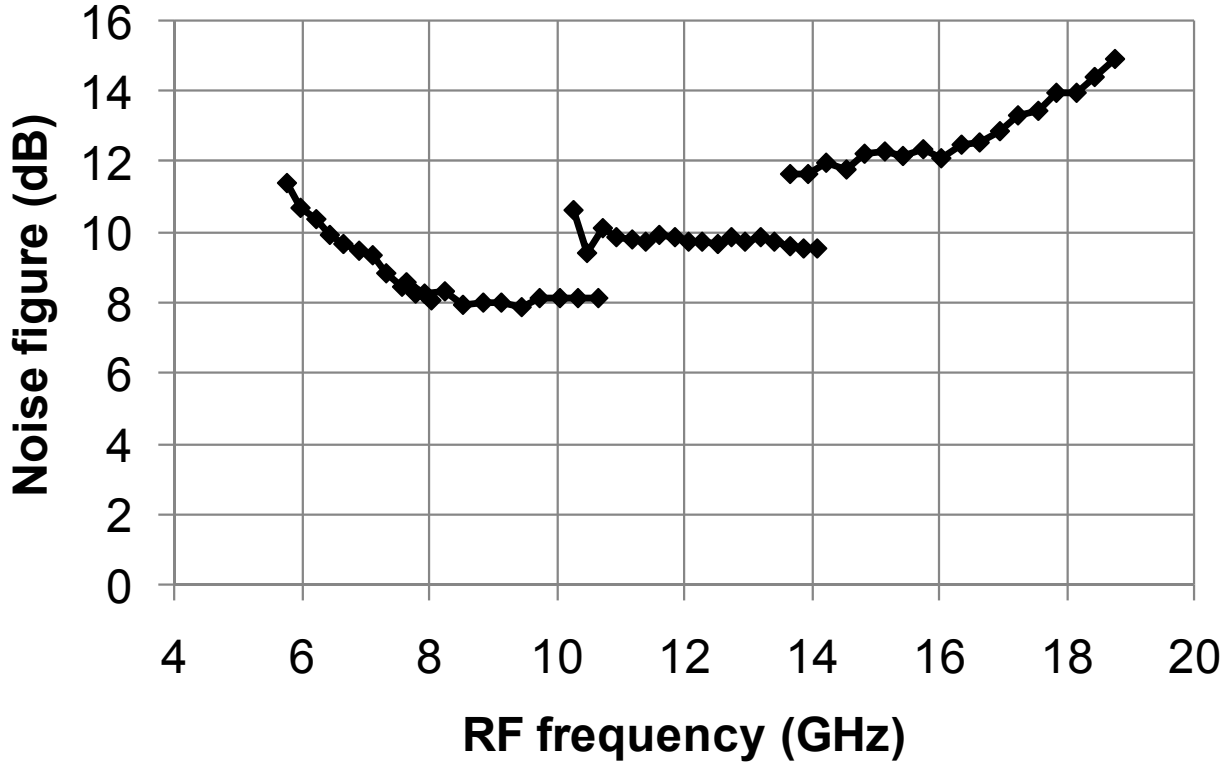

- Conversion gain = 16 ~ 24dB
- Pin_1dB = -25 ~ -15dBm
- IIP3 = -17 ~ -5dBm
- Discontinuities due to frequency band or scheme changes.

# RF Input Matching



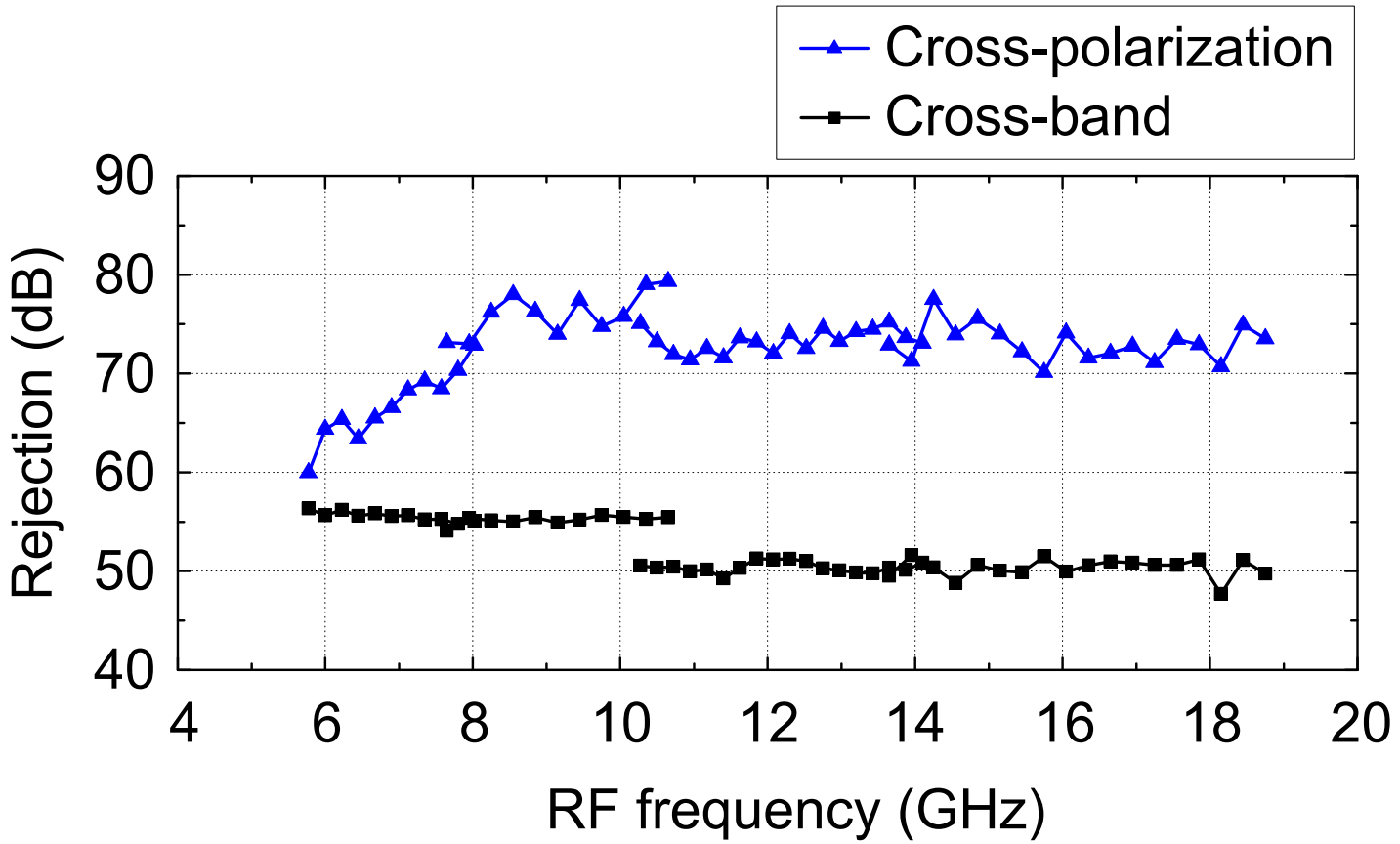

- Input matching insensitive to different TCA settings.

# Noise Figure




- NF = 8 ~ 14dB across the entire band.
- 2.6 ~ 3.1dB, considering the preceding wideband GaN LNA in the active antenna module (2.5dB NF, 20dB Gain).

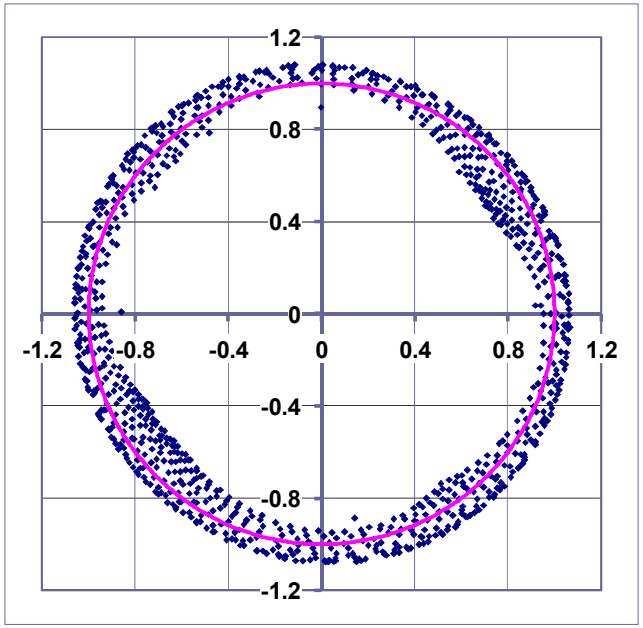
# Isolation Performance




- Good isolations between two bands (more than 48dB) and between two polarizations (more than 62dB).

# Phase Interpolation Performance

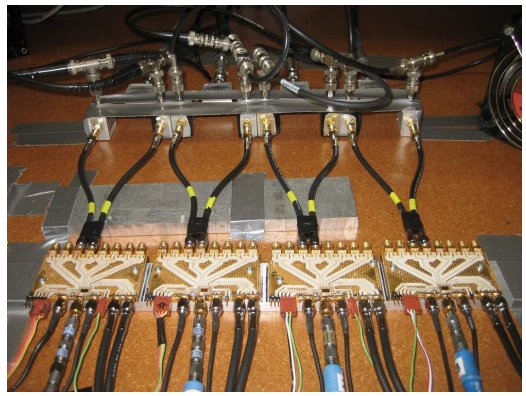
Measured constellation of interpolated baseband signal @18GHz

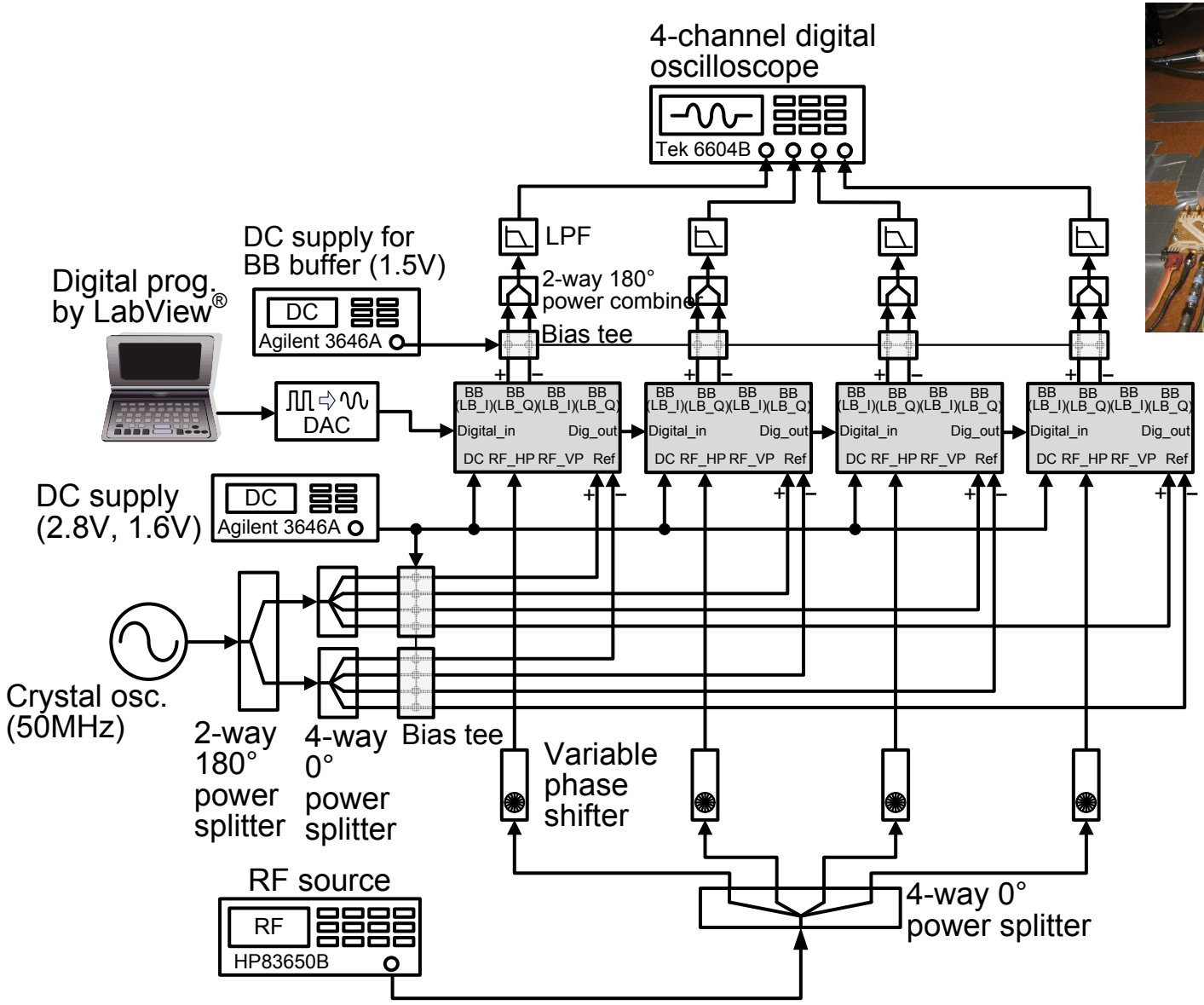



Phase interpolation performance summary

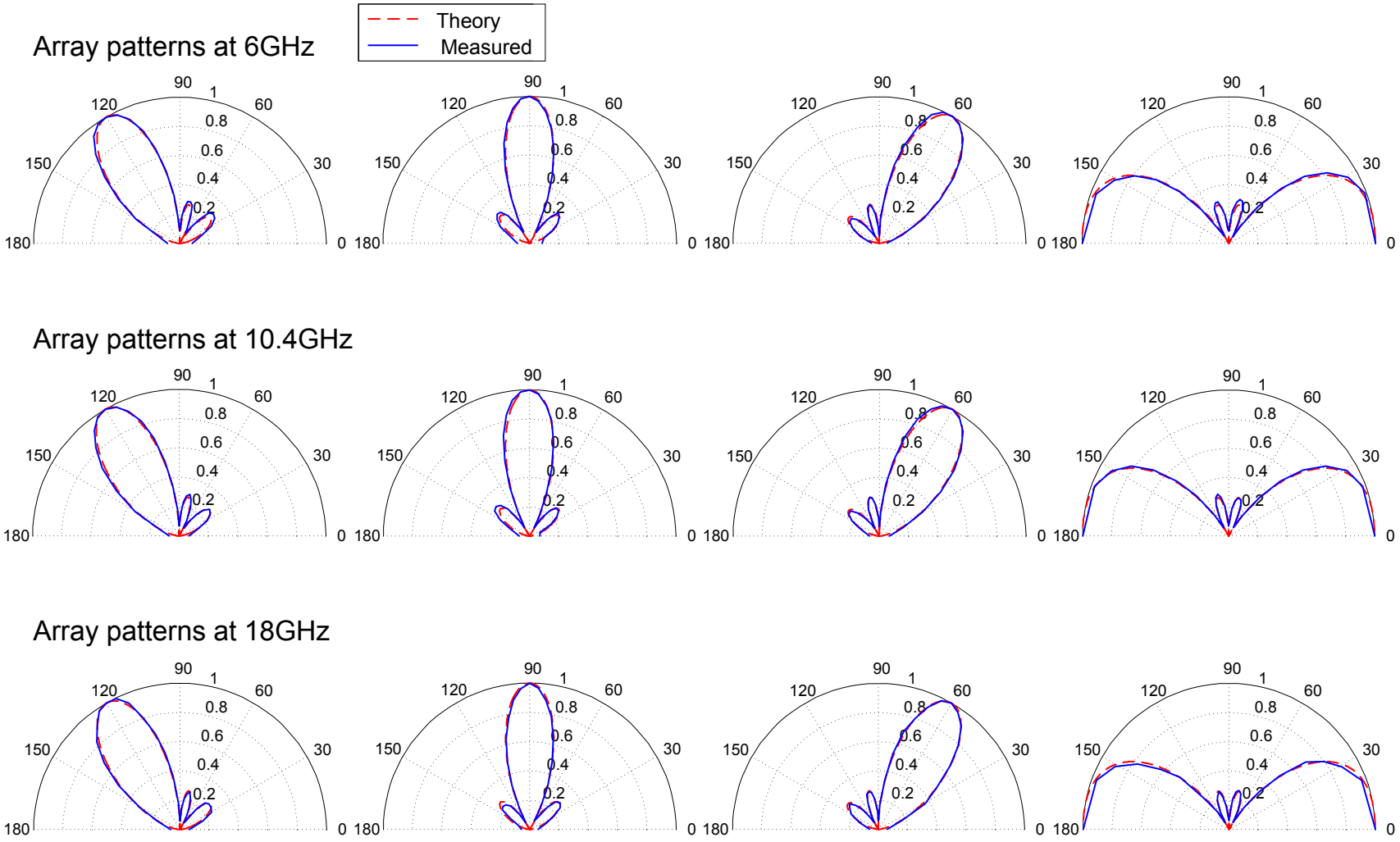
| RF Freq. | Phase Error RMS | Phase Error Max. | Amp. Variation RMS | Amp. Variation Max. |
|---|---|---|---|---|
| 6GHz | 0.5° | 2.6° | 0.4dB | 1.9dB |
| 10.4GHz | 0.2° | 1.2° | 0.2dB | 1.5dB |
| 14GHz | 0.3° | 1.4° | 0.2dB | 1.7dB |
| 18GHz | 0.2° | 1.3° | 0.5dB | 2.3dB |

# Array Test Setup



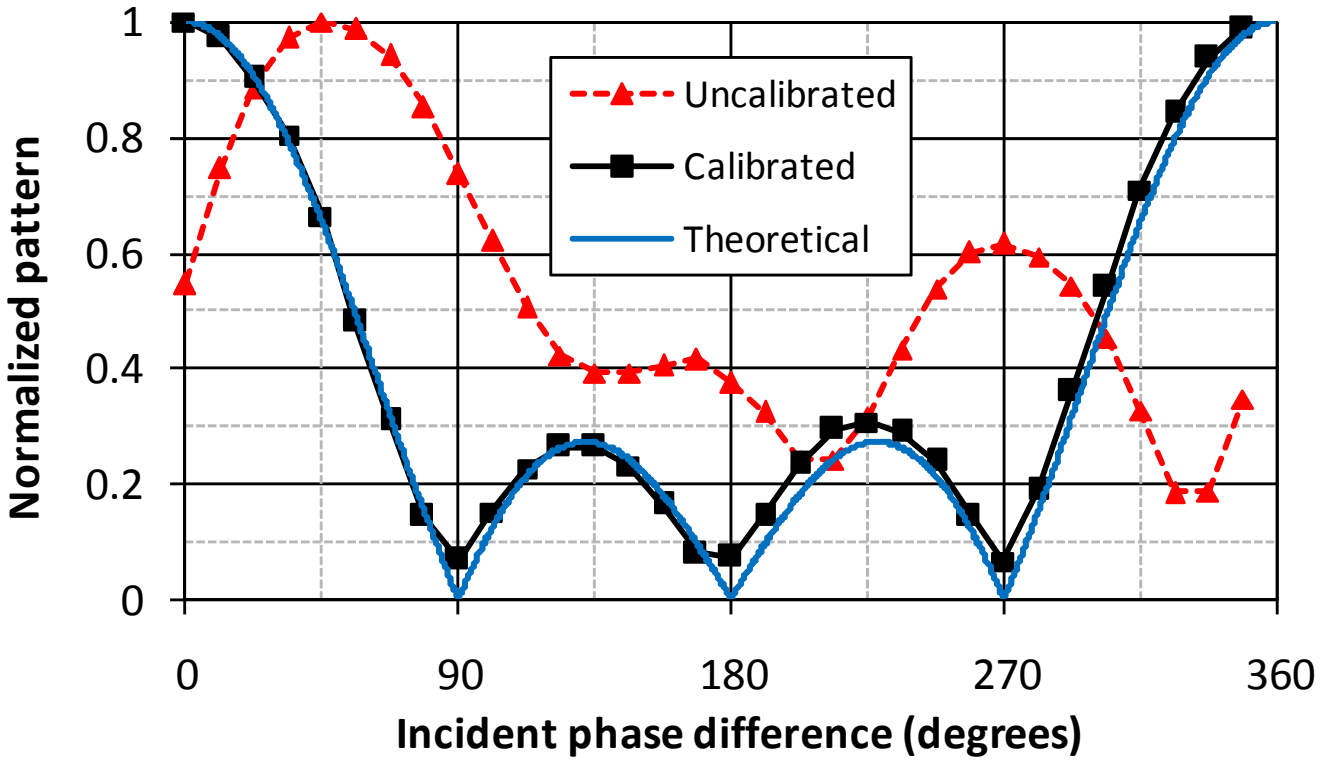


# Array Patterns



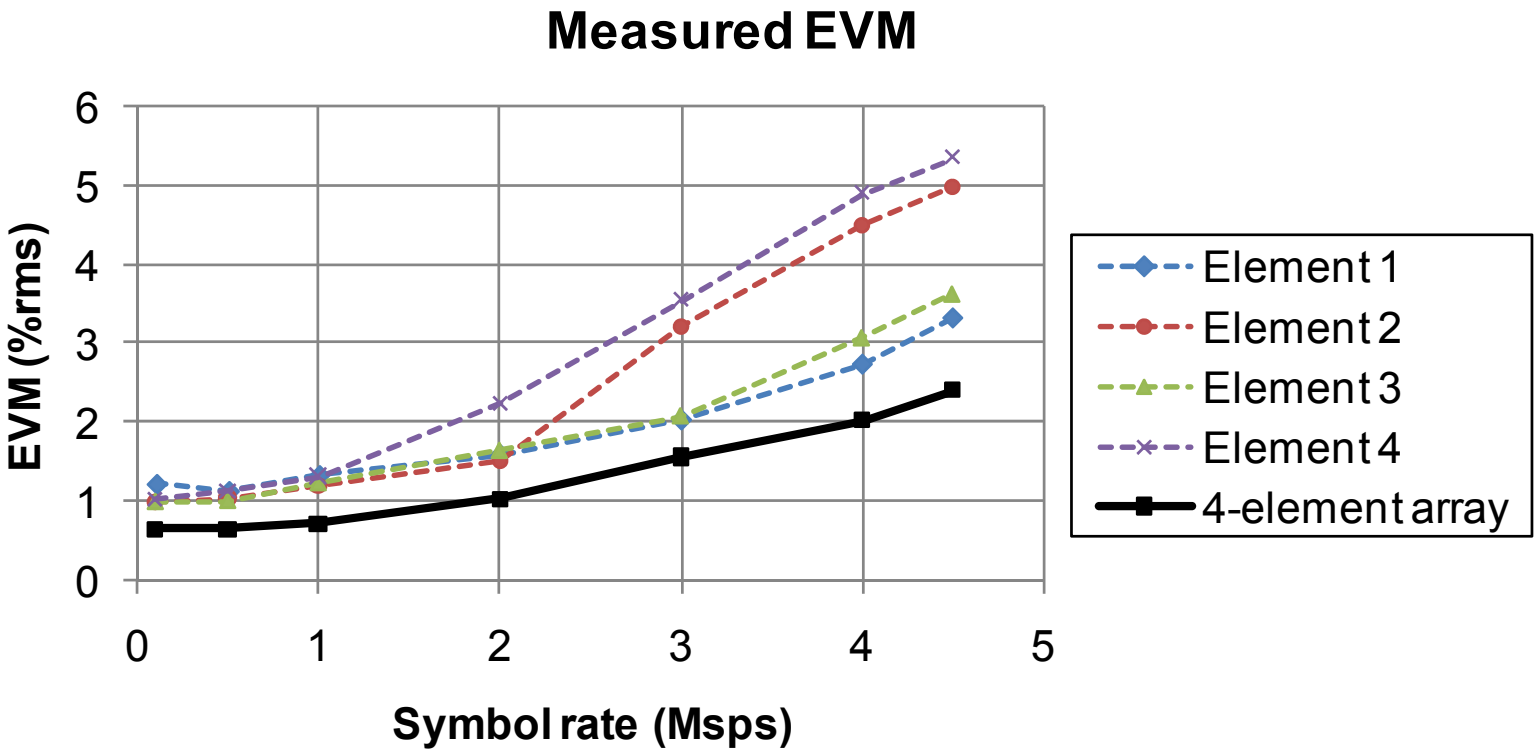

- Peak-to-null ratio > 21.5dB

# Phase Error Calibration



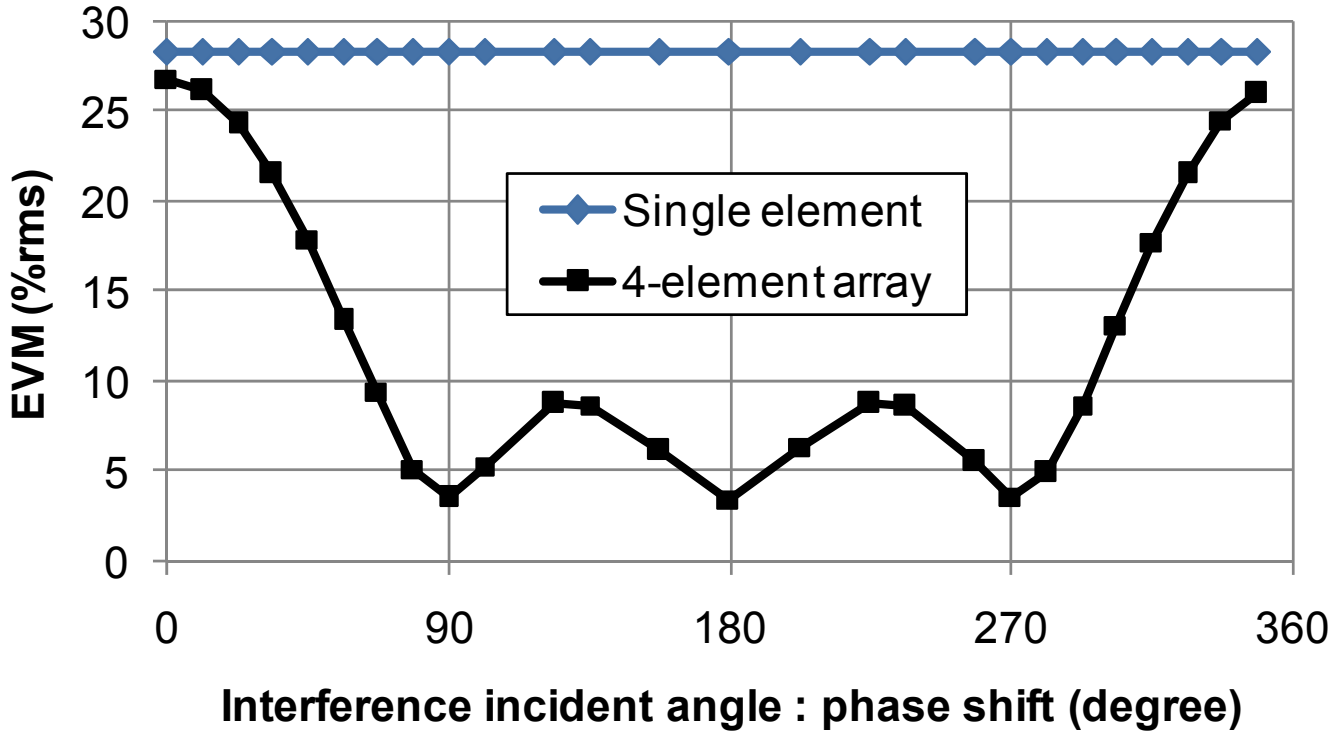

- One-time digital calibration of phase errors due to:
  - Mismatch, skews in ref signal distribution, element-by-element variation.
- On-chip phase shifting with fine resolution is essential.

# Digital Modulation Performance




- Modulation format: QAM32 @ 10.4GHz carrier.
- EVM improved in array.
  - I & Q mismatch improved after signal combining.
  - SNR improved after signal combining.

# Interference Rejection




- Desired signal: QPSK with 4Msps @ 10.4GHz, Pin = −35dBm, Incident angle fixed.
- Interference signal: FM with 100kHz @ 10.4GHz, Pin = −45dBm, Incident angle swept.
- Interference signal almost rejected at null positions.

# Performance Summary

## Receiver Element Performance

| | | |
|---|---|---|
| Conversion gain (6 – 18GHz) | | 15.7 ~ 24.7dB |
| Input-referred 1-dB compression (6 – 18GHz) | | −25.9 ~ −14.7dBm |
| Input-referred IP3 (6 – 18GHz) | | −17.0 ~ −5.2dBm |
| Input return loss (6 – 18GHz) | | > 9.5dB |
| Cross-polarization rejection (6 – 18GHz) | | > 63.4dB |
| Cross-band rejection (6 – 18GHz) | | > 48.8dB |
| LO leakage (6 – 18GHz) | | < −24.5dBm |
| Antenna-to-baseband noise figure† (6 –18GHz) | | 2.6 ~ 3.1dB |
| Phase shifting resolution (6 – 18GHz) | | < 5° (within 2dB amplitude variation) |
| RF channel spacing | | 225MHz (Div8 $LO_2$), 300MHz (Div2 $LO_2$) |
| Power consumption | RF and LO circuitry | 658mA @2.7V, 217mA @1.6V |
| | Baseband buffers | 328mA @1.5V |
| Technology | | 130nm CMOS |
| Die area | | 3.0×5.2 $mm^2$ |

## Phased-Array Performance (4 elements measured at 6-, 10.4-, and 18-GHz)

| | |
|---|---|
| Number of beams concurrently receivable | 4 |
| Phase shifting resolution per element | < 5° |
| Total phased-array gain | > 27.7dB |
| Beam-forming peak-to-null ratio | > 21.5dB |

# Conclusions

- The first tritave dual-band quad-beam phased-array receiver element in CMOS.
- RF front-end integrated from RF, LO to baseband.
- Easily scalable toward very large-scale phased arrays with low cost and high reliability.

# Acknowledgments


- Funding from Office of Naval Research and Raytheon Company.
- J. DeFalco and R. Healy of Raytheon Company.
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- Software assistance: Cadence, Agilent, Zeland, Sonnet, Ansoft.

For additional multimedia material: See http://www.isscc.org